UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULICS OF STRATIFIED FLOW--FIRST PROGRESS REPORT--AN ANALYSIS OF THE STATE OF THE ART AND A DEFINITION OF RESEARCH NEEDS

Report No. Hyd-563

Hydraulics Branch
DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

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ABSTRACT

A search of available literature on research in stratified flow revealed that the present state of research is dynamic, with many agencies and institutions in several countries involved. The report reviews the mechanics of stratified flow, including mathematical principles and criteria for similarity. Alternative instrumentation systems are discussed. The research activities of the Bureau of Reclamation are described and future research in hydraulics of stratified flow is proposed. Research by the Hydraulics Branch will consist of general studies concerning the influence of intake geometry on selective withdrawal from reservoirs. The initial studies will be extended to determine the effects of reservoir geometry. Gives 89 references.

DESCRIPTORS-- research and development/ reservoirs/ density currents/ *hydraulic models/ hydraulic similitude/ hydraulics/ instrumentation/ temperature sensors/ thermocouples/ *water quality/ *stratification/ thermistors/ Froude number/ velocity distribution/ turbulent flow/ temperature/ energy/ salinity/ sediment concentration/ flow/ turbidity/ bibliographies/ reviews
IDENTIFIERS-- Richardson number/ *selective withdrawal/ *stratified flow/ *thermal stratification/ uniform flow

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Report No. Hyd-563
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HYDRAULICS OF STRATIFIED FLOW--FIRST PROGRESS REPORT--AN ANALYSIS OF THE STATE OF THE ART AND A DEFINITION OF RESEARCH NEEDS

PURPOSE

The purposes of this report are to review the basic principles governing stratified flow in reservoirs and to define the present state of research in this subject.

SUMMARY

The present state of research in stratified flow is dynamic, with many agencies and institutions in several countries involved. Some areas which apparently require additional research are: the influence of reservoir and intake geometry on selective withdrawal and the optimization of intake design, model studies of particular reservoirs and correlation with prototype data, correlation of temperature distribution with dissolved oxygen in reservoirs, artificial alteration of density current distribution in reservoirs and estuaries, effects of hydraulic structures such as stilling basins on reoxygenation, and effects of earthquakes on movement of water in reservoirs.

Research is proposed for the Hydraulics Branch concerning selective withdrawal from reservoirs. Pilot studies will be aimed at determining the effects of intake and reservoir geometry on selective withdrawal. A temperature model with instrumentation consisting of thermistors will be used.

Modeling of stratified flow is governed by the Froude and Richardson numbers, which should be identical in the model and prototype. The Richardson number is a function of the ratio of the densities of the stratified layers and the Froude number of the layer being modeled. The Richardson number can also be considered as a densimetric Froude number, with the acceleration of gravity reduced by the ratio of the densities. When a distorted geometric model is used, the discharge should be increased to maintain turbulent flow, and the relative densities should be adjusted to maintain Richardson number similarity.

One source indicates that stratification due to temperature difference is the most advantageous method of modeling stratified flows. Determination of density differences by measurement of temperatures can be done very accurately. The same source recommends a thermocouple system for measurement of temperature.

INTRODUCTION

Population explosion and industrial growth have greatly increased the use of water for domestic, industrial, and agricultural purposes. Surface and underground sources of usable water are rapidly being depleted, resulting in increased attention to methods for conversion of sea water and brackish inland water to fresh water. Investigations are progressing in the control of water quality in surface streams. Temperature, dissolved oxygen content, mineral content, turbidity, and pH are among important properties to be considered in water quality control.

The control of temperature is important for the maintenance of fish and wildlife, irrigation, and industrial applications such as condenser water supply for thermal generating plants. Stratification due to temperature differences affects the absorption and transport of sewage effluent, the movement of sediment, and the distribution of dissolved oxygen. On a very large scale, the movement of temperature stratified layers in the oceans affects continental climatic conditions.

Dissolved oxygen in streams is necessary for biological degradation of sewage and industrial wastes, and stream and reservoir oxygen content affects the growth of fish life.

Density variations caused by dissolved salts are considerations in the design of locks between the sea and fresh water channels to control intrusion of salt water. Sea water intrusion into tidal estuaries and coastal ground-water aquifers has long been a serious problem affecting water quality.

Knowledge of the movement of sediment in reservoirs (turbidity currents or density underflows) is necessary for the determination of sediment deposition and sluicing operations. Proper design of outlet structures can ensure the release of clear water with desirable temperature and dissolved oxygen content for downstream users.

The Bureau of Reclamation has shown increasing awareness of the problems of water quality control. Among these problems have been sediment movement in reservoirs, salinity of riverflows allocated to irrigation, and salinity intrusion in estuaries. Increasing attention is being given to reservoir limnology and to selective withdrawal from reservoir storage for the control of downstream temperature and dissolved oxygen content. Growing use of USBR impoundments for domestic water supply is giving added importance to water quality control.

MECHANICS OF STRATIFIED FLOW

Portions of the discussion presented in this section were extracted from Section 26 of Streeter's "Handbook of Fluid Dynamics" [6]. 1/

General

Most stratified flow problems are directly concerned with two-layered systems. Multilayered systems are less common and have application primarily to problems in meteorology. An extension of the multilayered system is a system with a continuous density gradient. Uniform flow in a two-layered system is usually associated with density currents, which are commonly known as gravity currents or underflows. Examples of this phenomenon are cool-water underflows in streams and reservoirs, underflows of sewerage effluent, and density currents of suspended sediment in reservoirs. Uniform two-layered flow systems can exist in either a laminar or a turbulent state.

Nonuniform flow problems in two-layered systems include the movement of saline wedges in salt water intrusion problems, the formation of subsurface hydraulic jumps during filling of locks, and the motion of waves at the interface between two layers. Interfacial mixing due to wave motion must also be considered. The stability of the interface is important in the mechanism of selective withdrawal, with specific reference to the withdrawal of layers of known temperature in a stratified reservoir.

After mixing at the interface between fluids of different densities is well established, the mechanics of diffusion become important. Diffusion in motionless, stratified systems is classified as unsteady and one dimensional, and is analogous to one-dimensional heat conduction in a thin rod. In estuary studies the diffusion and accompanying distribution of salinity can be used to predict the distribution of other "contaminants," such as dissolved oxygen.

Highly stratified tidal estuaries (where the density differences are large) tend to shift toward a vertically homogeneous (no stratification) type through a process of steady-state diffusion, dependent upon the velocity of the fresh water and the rate of energy dissipation. Another application is the diffusion of jets discharging into a fluid of different density, as in sewerline ocean outfalls or atmospheric pollution problems.

Mathematical Principles

Energy Concepts

This discussion will be limited to a two-layered system or, with certain limitations, to any two layers in a more complex system. A definition

1/Numbers in brackets refer to references listed at the end of this report sketch is shown in Figure 1. It is assumed that the upper layer is static and the lower layer is moving at a velocity u. The densities of the upper and lower layers are designated by ρ_1 and ρ_2, respectively. The energy equation between two points, a and b, on the interface is

$$p_a + \rho_2 \frac{u_a^2}{2} + \rho_2 g Z_a = p_b + \rho_2 \frac{u_b^2}{2} + \rho_2 g Z_b \tag{1}$$

with friction losses neglected, or when all terms are divided by γ

$$h_a + \frac{u_a^2}{2g} + Z_a = h_b + \frac{u_b^2}{2g} + Z_b$$

In the upper layer:

$$p_a + \rho_1 g Z_a = p_b + \rho_1 g Z_b \tag{2}$$

Subtracting (2) from (1):

$$\rho_2 \frac{u_a^2}{2} + \rho_2 g Z_a - \rho_1 g Z_a = \rho_2 \frac{u_b^2}{2} + \rho_2 g Z_b - \rho_1 g Z_b$$

Simplifying:

$$\rho_2 \left(\frac{u_b^2}{2} - \frac{u_a^2}{2} \right) = (\rho_2 - \rho_1)(g Z_a - g Z_b)$$

$$H = Z_a - Z_b$$

$$\rho_2 \left(\frac{u_b^2}{2} - \frac{u_a^2}{2} \right) = (\rho_2 - \rho_1) gH$$

Assign

$$g' = \frac{(\rho_2 - \rho_1)}{\rho_2} g = \frac{\Delta\rho}{\rho_2} g$$

Then

$$\frac{u_b^2 - u_a^2}{2} = g'H \tag{3}$$

At a free surface (air-water interface), $\Delta\rho \approx \rho_2$. Therefore,

$$\frac{u_b^2 - u_a^2}{2} = gH \tag{4}$$

Thus, at any point in the lower layer, the movement of fluid is governed by the reduced gravitational force and is described by the dimensionless parameter

$$F' = \frac{u}{\sqrt{g'Z}} \tag{5}$$

which is known as the densimetric Froude number.

Uniform Flow in a Stratified Fluid

The equilibrium equation is

$$\tau_o + \tau_1 = \Delta\,\rho\,g\,h_2\,S \tag{6}$$

where τ_o = bottom shear,

τ_1 = shear at the interface,

h_2 = vertical depth of the bottom layer,

S = bottom slope.

Refer to the definition sketches in Figures 2 and 3. It is assumed that the bottom layer is moving under a static upper layer of large extent, as compared to the bottom layer. The velocities induced in the upper layer by movement of the bottom layer may be neglected. It is also assumed that the flow is two dimensional and that the velocity distribution is fully developed. The equilibrium equation (6) describes these conditions. The system may be considered as analogous to flow between parallel boundaries; in this case the bottom is fixed and the interface is assumed to be moving at a velocity, u_1. The shear stress varies linearly from τ_o at the bottom to zero at the point of maximum velocity, u_{max}, then to τ_1 at the interface. The interface shear is therefore a constant proportion of the bottom shear.

$$\tau_1 = \alpha\,\tau_o, \tag{7}$$

where the constant α depends on the location of the maximum velocity (see Figure 3).

$$\alpha = \frac{1 - 2\,Z_m/h_2}{1 + 2\,Z_m/h_2} \tag{8}$$

Substitution of Equation (7) in Equation (6) gives

$$\tau_o = \Delta\,\rho\,g\,\frac{h_2}{1 + \alpha}\,S \tag{9}$$

τ_o may also be expressed as

$$\tau_o = \frac{f}{4}\,\rho_2\,\frac{\bar{u}^2}{2} \tag{10}$$

where f is the Darcy-Weisbach resistance coefficient, and $\bar{u}$ is the average velocity.

By equating Equations (9) and (10) and solving for $\bar{u}$,

$$\bar{u} = \sqrt{8g'\,\frac{h_2 S}{f(1 + \alpha)}}, \tag{11}$$

where $g' = \frac{\Delta\rho}{\rho}\,g$ as defined earlier.

Equation (11) can be recognized as a generalized form of the equation for uniform flow in open channels:

$$\bar{u} = \sqrt{\frac{8g}{f}}\sqrt{R\,\frac{h_f}{L}}$$

where R is the hydraulic radius and $\frac{h_f}{L} = S$

The usual form is $\bar{u} = C\sqrt{RS}$, the Chezy equation.

Velocity distribution in laminar flow.--In laminar flow, viscous forces affect the shear stress ratio described above. The friction coefficient, f, varies with the Reynolds number, Re. A dimensionless parameter, J, which indicates a ratio of gravity and viscous forces, is included in the expression for the laminar velocity distribution.

$$J = \frac{(F_2')^2}{Re_2 S}$$

where F' is the densimetric Froude number derived earlier. (The subscript 2 refers to the bottom layer.)

$$F_2' = \frac{\bar{u}}{\sqrt{g' h_2}} \quad \text{and} \quad Re_2 = \frac{\bar{u}\, h_2}{\nu}$$

The dimensionless form of the velocity distribution is

$$\frac{u}{\bar{u}} = 1 + 2\frac{Z}{h_2} - \frac{1}{2J}\left[\left(\frac{Z}{h_2}\right)^2 + \frac{1}{3}\frac{Z}{h_2} - \frac{1}{12} \right] \tag{12}$$

Differentiation of this equation gives the relation between the interface velocity and the maximum velocity,

$$\frac{u_i}{u_{max}} = \frac{12J - 1}{12J^2 + 4J + \frac{1}{3}} \tag{13}$$

The lower critical value of Re for turbulent flow has been estimated to be about 1,000.

Turbulent flow in stratified fluids.--Velocities in turbulent flows of stratified fluids may be estimated by adjustment of Equation (11). The problem is not subject to exact analysis. The term $(1 + \alpha)$ in Equation (11) indicates the necessary increase in f due to the presence of the interface ($\alpha = 0$ for free-surface flows). The value of f is obtained from the Moody diagram for flow in conduits by using $4\, h_2$ as the hydraulic radius, then adjusting this value with the factor $(1 + \alpha)$. Experiments have shown an average value of α of about 0.43, based on a maximum velocity occurring at a depth of approximately $0.7\, h_2$. No systematic variation with the Reynolds number $(V \cdot 4\, h_2/\nu)$ for Reynolds numbers less than 10^5 was noted.

Nonuniform Flow in Stratified Fluids

Knowledge of the mechanics of nonuniform flow in stratified fluids is important in analysis of saline intrusion in estuaries and the circulation of cooling water in the vicinity of a thermoelectric powerplant. The derivation of the governing equations is relatively lengthy and will not be presented here. It will suffice to say that generally problems of nonuniform flow in stratified fluids are related to changes in flow regime caused by control sections consisting of fresh water barriers, artificial barriers, or changes in cross-sectional shape or bottom profile. Again, these problems are analogous to those for free-surface flow.

The purpose of this section on the mathematical principles of the mechanics of stratified flow has been to present the basic equations governing the motion of stratified fluids and to illustrate their similarity with corresponding equations for free-surface flow. The more specific topics of sediment transport, internal-wave motion, interfacial mixing, multilayered systems and continuous-density gradients, and diffusion will not be discussed in this report. A detailed discussion of these topics is included in Section 26 of Streeter's Handbook of Fluid Dynamics, cited earlier.

Similitude and Modeling Laws

Criteria for Similarity

The densimetric Froude number was discussed in the preceding section and was presented as Equation (5),

$$F' = \frac{\bar{u}}{\sqrt{g'Z}}$$

The criterion for similitude is that the densimetric Froude number of the model and prototype must be identical. An alternate expression, which is also widely used, is the Richardson number, Ri, expressed by

$$Ri = \frac{\Delta\rho}{\rho} \cdot \frac{gZ}{u^2} \tag{14}$$

which is equal to $\dfrac{1}{(F')^2}$

The Richardson number may also be written

$$Ri = \frac{\Delta\rho}{\rho} \cdot \frac{1}{F} \tag{15}$$

This form suggests that, if the model is scaled according to the Froude law, the model density differences must correspond to the prototype density differences to ensure Richardson similarity.

In a detailed cooperative study by the TVA and the Corps of Engineers [41] the equations of motion and the conservation of mass equation were manipulated to derive the densimetric Froude number for a flow in which the density varies linearly over the entire depth:

$$F' = \frac{u_o}{\sqrt{g \frac{\Delta\rho}{\rho} h}} \tag{16}$$

where u_o = average velocity,

$\bar{h}$ = flow depth,

ρ = density at bottom,

$\Delta\rho$ = change in density over h

The equation is essentially identical to Equation (5) for a two-layered system.

M. B. Abbott and I. Larsen [43] discuss the modeling of a shallow surface fluid spreading over another fluid and state that it is sufficient for the densimetric Froude numbers of the model and prototype upper layers to be equal. Their F' is in the same form as Equation (16). They further explain that to correctly model two layers the densimetric Froude number

$$F' = \frac{u_1 - u_2}{\sqrt{\frac{\Delta\rho}{\rho_2} g(h_1 + h_2)}} \tag{17}$$

should be used, where the subscripts 1 and 2 refer to the upper and lower layers, respectively.

In summary, when modeling a system with a continuous density gradient or either layer of a two-layered system, a densimetric Froude number with a form similar to Equation (16) must be equal in model and prototype. If both layers of a two-layered system are modeled, Equation (17) should be used.

Chen [46] discusses model simulation of thermal stratification in shallow cooling reservoirs, with particular reference to heat exchange at the surface and the effect of stratification on flow patterns. Several excellent model-prototype comparisons are presented. Chen points out that when the density differences in model and prototype are not equal it is impossible to satisfy both the Froude and Richardson criteria. He suggests that the Froude criterion can be neglected, since its importance is generally limited to the region in the immediate vicinity of the reservoir inlet and the overall reservoir flow pattern is not greatly affected. It seems to the writer that the Froude criterion should also be considered in the vicinity of an outlet works intake, for example, when studies are being made of the intake tower geometry. Possibly the error can be minimized by maintaining small density differences and attributing less importance to the Richardson criterion. In other words, the similitude criterion would depend on the type of problem being studied.

A third criterion for similarity is that the Reynolds' number in the model should be greater than a certain critical value based on the flow pattern. Chen raises the important question as to what characteristic length should be used in the dimensionless ratio. He suggests avoiding this difficulty by dropping the length term and using the ratio $\frac{Q}{\nu}$ to replace the Reynolds' number. This ratio has the dimensions of feet. Therefore, the similarity rule is $\left(\frac{Q}{\nu}\right)_m > \left(\frac{Q}{\nu}\right)_{cr}$, where the subscripts refer to model and critical, respectively. The rule reduces further to $Q_m > Q_{cr}$. Discharges above the value of Q_{cr} will result in the same general flow pattern. Q_{cr} is governed by the model size, water depth, reservoir topography, relative positions of the inlet and outlet, etc. Chen suggests that the value of Q_{cr} must be estimated from past experiments, then checked in preliminary model tests.

Scale Distortion

D.I.H. Barr [45] states that if the model scale must be distorted because of laboratory space limitations or other reasons, the discharge should be increased to maintain turbulent flow and allow the viscous forces to be neglected. If the discharge is increased, the relative densities should be adjusted to maintain Richardson similarity.

If the ratio of the increased discharge to the discharge computed for similarity is defined as

$$M = \frac{Q_m}{Q_{m(\text{computed})}}$$

then to maintain the original Richardson number, the model relative density is adjusted by

$$\left(\frac{\Delta\rho}{\rho}\right)_m = M^2\left(\frac{\Delta\rho}{\rho}\right)_p \tag{18}$$

where m and p designate model and prototype, respectively.

Barr suggests that exaggeration of the horizontal scale is necessary for correct simulation of the rate of spread of a stratified layer. The appropriate exaggeration is determined through the use of a congruency diagram, an example of which is presented in Barr's article. Barr states that this diagram requires additional development.

Density differences may be due to temperature, salinity, or turbidity. Temperatures can be measured by thermometer, thermocouple, or thermistor. Measurement of salinity is commonly accomplished by determination of the conductivity of the sample. Turbidity measurements are made by use of photoelectric cells or various mechanical devices for in situ measurements. Diffusion of stratified layers can be measured with radioactive isotopes and Geiger counters.

Measurements can be made in situ or by continuous abstraction recording. Continuous abstraction recording, which consists of continuous withdrawal of a sample, has generally been restricted to salinity measurements. This method would probably be unsuitable for temperature measurement because of heat losses.

Choosing a Recording System

Barr [87] suggests that the following factors should be considered in the choice of a recording system:

1. Accuracy over desired range of density difference.

2. Speed of response to changes in the measured variable.

3. Ability to localize the point of measurement.

4. Disturbance to the flow.

5. Whether recording is automatic or by observer; if automatic, whether continuous or intermittent; if intermittent, determination of suitable interval.

6. Number of points which can be observed during one test.

7. Whether measurements are in situ or after abstraction; if the latter, whether continuous or in samples; and the comparative value of the results which might be obtained by these differing approaches.

8. Adaptability to differing aspects of nonhomogeneity studies.

9. Ease of use, including ease of interpretation of recording.

Use of Temperature Difference to Induce Stratification

Barr prefers the use of temperature, rather than salinity or turbidity, to simulate stratification in models. The primary advantage of this method is that if temperatures can be determined to $\pm 0.1°$ F., for example, the density difference can be found to an accuracy of better than one part in ten thousand. There is no fully comparable method available for measurement of density differences due to salinity or turbidity. The primary disadvantages in the use of temperature as the controlling variable are:

1. Variations in viscosity. This effect is negligible if the temperature difference is small.

2. Nonlinearity of the temperature-density relationship. The relation is approximately linear only between approximately 25° and 60° F.

3. Heat losses. The problem of heat transfer between layers can be minimized by maintaining a small temperature difference. Heat exchange through the model walls can be controlled by attempting to maintain the water temperature approximately equal to the room temperature and by insulating the model, or by air-conditioning the room.

Temperature Measurement by Thermocouple or Thermistor

Barr recommends a thermocouple system for the measurement of temperatures, stating that such a system has the following advantages:

1. Good accuracy for the purpose intended as compared with other methods.

2. Identical calibration for any number of probes.

3. Duplication of probes and probe systems at low cost.

4. Equally applicable to the recording of local temperature changes due to individual turbulence eddies or to the recording of relatively long-period average values.

5. Speed in obtaining data from many points.

A thermistor system has the same advantages as the thermocouple system.

The thermocouple or thermistor system would probably include a switching arrangement so that sets of probes could be read in quick succession. The temperatures would be recorded on a multichannel oscillograph or a printer.

Other Devices for Temperature Measurement

G. G. Watson [89] lists several other devices, most of which are for approximate measurements, including paints, papers, pellets, contact-thermography, optical pyrometry, radiation pyrometry, projection thermography, photographic techniques, electromagnetic effects, and metallurgical techniques.

Use of Salinity Difference to Induce Stratification

The primary advantage of the use of salinity difference over temperature difference to induce stratification is elimination of the problem of heat losses. One disadvantage is that the density cannot be determined as accurately as temperature. Another disadvantage is that simultaneous measurement of the salinity of several points in the fluid cannot be performed as expeditiously as can temperature measurement.

The use of salinity for variations in density could probably be accomplished with relatively simple mixing equipment; however, control of the density might be more difficult than with a heat system.

Salinity Measurement by Conductivity

An external potential source is necessary to measure the conductance of a solution. Sensors currently being used for measurement of conductivity include platinized electrode sensors, potentiometric sensors, and electrodeless sensors. The three types are described in detail in a paper by A. F. Mentink [88]. Apparently, the only sensor which might retain sufficient accuracy for use in a laboratory study is the platinized electrode. Bridge circuitry is necessary for this method. Since conductivity is dependent on temperature, some type of temperature compensation must also be included in the system. Mentink states that temperature effects are, generally, automatically compensated by using thermistor-resistor networks. The measurement of conductivity does not seem to offer any advantages with respect to instrumentation, as compared to the measurement of temperature.

PRESENT STATE OF RESEARCH (1966)

Research in stratified flow is currently being carried out by many agencies and institutions. Massachusetts Institute of Technology, California Institute of Technology, and many other domestic and foreign educational institutions have accomplished basic and applied research in the field, in many cases in cooperation with Government agencies.

The U.S. Public Health Service, the Tennessee Valley Authority, the U.S. Army Corps of Engineers, the National Bureau of Standards, the U.S. Bureau of Reclamation, and many foreign agencies have conducted investigations in various phases of water quality control and stratified flow.

ASCE Seminar on Water Quality Management

In July of 1965, a Seminar on the Hydraulic and Engineering Aspects of Water Quality Management in River and Reservoir Systems was held in Chattanooga, Tennessee, under the sponsorship of the American Society of Civil Engineers. The topics selected for discussion were: (1) impoundments, (2) rivers, (3) estuaries, (4) models and specific project investigations as tools for solving problems, (5) data, instrumentation and automation, (6) quality modification by physical controls, and (7) systems and optimization. It was concluded that a need exists for improved designs of outlet structures with possible inclusion of devices such as floating weirs or submerged barriers. A special category of improved outlet design is concerned with the design and testing of multiple outlets for existing structures. There is an apparent lack of data on model-prototype conformance. It was also noted that data are lacking on the exchange of energy and gases (such as dissolved oxygen) across interfaces.

It was the consensus of the seminar participants that development of appropriate instrumentation is in its early stages, particularly with regard to portable equipment.

Need exists for the application of the engineering sciences to quality modification by general techniques such as aeration devices, skimmers, environmental control, selective withdrawal, and mixing under stratified conditions.

Apparent Research Needs, Based on a Literature Search

Extent of past and present research.--Among the primary areas of the mechanics of stratified flow which have been or are being investigated are: wave propagation in stratified flow; density currents and siltation in docks and tidal basins; salinity intrusion; turbulent entrainment in stratified flows; effects of currents, salinities and riverflow on river regimen; motion of saline fronts in still water; vertical mixing in stratified flowing water; temperature distribution in stratified flow; velocity distribution at the stratification interface; stratified flow in saturated porous media; density currents in reservoirs; flow of saline water from locks into fresh water channels; recirculation of cooling water in rivers and canals; critical flow and hydraulic jumps in a multilayered system; atmospheric flow problems; stability of layered flows; selective withdrawal, including submerged sluice control of stratified flow and thermal density underflow diversion; diffusion of stratified flows; and oxygen balance in estuaries. It is noted that many of the general areas listed overlap each other. The purpose of including this list is to acquaint the reader with the wide variation in past and present research in stratified flow.

Areas needing additional research.--Some areas which apparently have not been investigated or which have been investigated to a relatively small extent are: the influence of reservoir and intake geometry on selective withdrawal and the optimization of intake design, model studies of particular reservoirs and correlation with prototype data, correlation of temperature distribution with dissolved oxygen in reservoirs, artificial alteration of density current distribution in reservoirs and estuaries, effects of hydraulic structures such as stilling basins on reoxygenation of rivers, and effects of earthquakes on movement of water in reservoirs.

The topics listed in the preceding paragraph are based on an independent literature study conducted by the writer. It is interesting to note that several areas requiring additional research in the writer's opinion also agree with the findings of the previously described ASCE seminar.

Research Activities of the Bureau of Reclamation

Observation of the movement of stratified flows in Bureau of Reclamation reservoirs began about 30 years ago in Lake Mead, and was concerned with the movement of density currents along the reservoir bottom. The extent of prototype measurement has grown until, during the past few years, detailed measurements of water chemistry have been made throughout Lake Mead. These studies are being accomplished under the supervision of the Chemical Engineering Branch of the Division of Research in Denver. Measurements of temperature and water chemistry also are being made in Cheney Reservoir by the city of Wichita under contract. This reservoir offers a unique opportunity to obtain very useful data as it utilizes multiple outlets. Also, all releases pass through a treatment plant so that discharge rates and quality may be very closely monitored. Measurements of conductivity and temperature are also being made in Foss Reservoir, Oklahoma.

The Chemical Engineering Branch hopes to extend the Lake Mead measurements upstream to Lake Powell and eventually to all reservoirs in the Colorado River Basin. This comprehensive study would allow an analysis of the effects of all reservoirs on the water quality throughout an entire river basin.

Future plans also include experiments on the natural reaeration rates of streams downstream from dams, in particular for fast-moving streams which prevail in the Bureau of Reclamation regions. Similar studies have been made by the Tennessee Valley Authority on slow-moving streams. It is also hoped to determine the effect of impoundments on the water quality of streams by making quality measurements on a selected stream before and after dam construction.

Region 2 of the Bureau of Reclamation is engaged in a water quality program in California. The program includes determination of the effects of diversion from the Sacramento River on water quality in the Sacramento River Delta, effects of effluents from drains, reservoir turbidity, control of water temperature in reservoir releases, reservoir algae control, and other problems. Region 2 uses a mobile water quality monitoring van which contains instrumentation for the measurement of dissolved oxygen, pH, conductivity, air and water temperature, sunlight, and turbidity. Regions 1 and 4 are also engaged in water quality monitoring programs.

Research by the Hydraulics Branch has been limited to an electric analogy study of the effects of selective withdrawal from Lake Mead; hydraulic, electric analogy, and mathematical studies of salinity intrusion in an estuary; a general investigation of the hydraulics of density currents; a study of cooling water circulation for a thermal generating plant; and a limited study of stratified flow over weirs. No research in the hydraulics of stratified flow has been conducted since 1956.

To the best of the writer's knowledge, no other significant studies have been made.

PROPOSAL FOR RESEARCH BY THE HYDRAULICS BRANCH

It is proposed to begin a general study of the influence of intake geometry on selective withdrawal. The initial study will be made in a laboratory flume to develop testing procedures and instrumentation and to evaluate methods of inducing stratification. Some basic data on the mechanism of withdrawal from several levels in a reservoir can also be obtained at this time. The methods will then be applied to a larger model, probably of an existing reservoir, in an attempt to simulate observed prototype stratification and study the effects of reservoir and intake geometry. It is hoped that direct model-prototype comparisons can be made.

Facility Requirements

Temperature difference will be used to induce stratification. The test flume will be located in a relatively compact area so that, if excessive heat losses appear to be a problem, the area can be enclosed and isolated from the rest of the laboratory. A tentative layout of the test facility is shown in Figure 4.

The initial tests will be made with two-layer stratification. This will require water sources of two different temperatures. A small centrifugal pump will be used to recirculate the layer under study, which will probably be cooler than the static layer and slightly cooler than the room temperature. Increases in temperature caused by heat transfer from the warmer layer through the walls of the model, or from the pump, will be compensated by enclosing a section of the circulation pipe in a temperature cooling tank. The tank will contain cool water flowing at a rate depending upon the required cooling rate. Three sides and the bottom of the testing flume will be insulated by a 6-inch air space between two 3/4-inch plywood sheets. The fourth side of the flume will consist of 2-inch-thick plexiglass to permit visual observation of the stratified layers and to minimize heat transfer from the room. The top of the flume will consist of 1/2-inch-thick plexiglass located 6 inches above the water surface. The resulting air space will be saturated, and at the same temperature as the water to prevent heat transfer caused by evaporation at the water surface. Measurements of temperature will be made through instrumentation ports in the plexiglass cover.

The source of the warm layer will be the subfloor water storage which is used for hydraulic model tests. This water has a temperature of about 17° to 20° C which corresponds to a density of approximately 0.9988 to 0.9982 gm/ml. Water from the city supply lines, which has a temperature of about 7° C (density of approximately 0.9999 gm/ml) will be used for the more dense, lower layer. The disadvantage of this temperature range is that it is in the upper portion of the temperature-density curve, Figure 5.

As the studies progress, it will become necessary to vary the temperatures to perform tests for differing density ratios and to investigate multilayered or continuous density gradient situations. This variation could be accomplished either by heating or cooling.

Heating may be required to move the temperature-density relation into the more linear portion of the curve. This heating will be accomplished with immersion heaters with thermostatic control. Dyes will be mixed at this time to facilitate observation of the layers.

Instrumentation Requirements

Thermistors will probably be used for temperature measurement. Many types are commercially available. The sensors can be mounted on vertical probes or installed through the flume walls and can be used with the oscillograph recorders or the digital printer presently available in the laboratory.

Temperature controllers will also be necessary for use with immersion heaters or similar heating devices. The controllers monitor the temperature and actuate relays to operate the heaters when the temperature departs from the preset reference temperature. One channel of control is required for each temperature or density layer.

Discharge rates and water surface levels will be determined with existing laboratory meters and gages. Velocities will be measured with miniature current meters or by time-lapse photography of the movement of dye tracers.

It is hoped that some type of automatic device can be devised to eliminate the necessity for manual control and laborious data monitoring. A scanner would be required to sample data from each of several output channels at specified time intervals.

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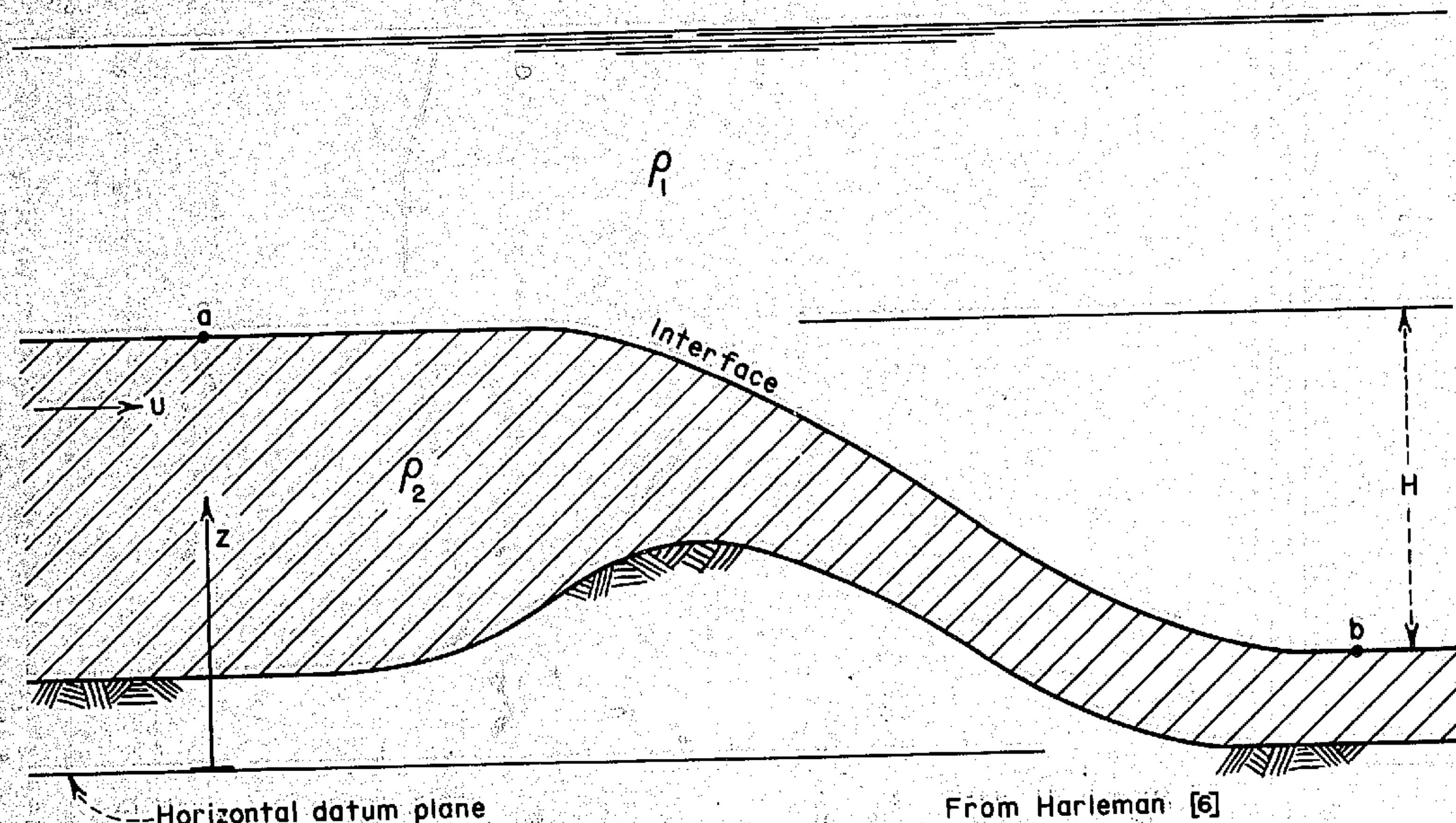
All listed references were not consulted in the preparation of this report. Many were derived from other references and were included in this listing because the title suggested possible application to this research. Most of them contain many other references. The purpose of compiling the selected list is to provide a basic source of information for the present research and for future investigators.



STRATIFIED FLOW IN RESERVOIRS

FIGURE 1—DEFINITION SKETCH
GRAVITY FLOW IN A TWO-LAYERED SYSTEM

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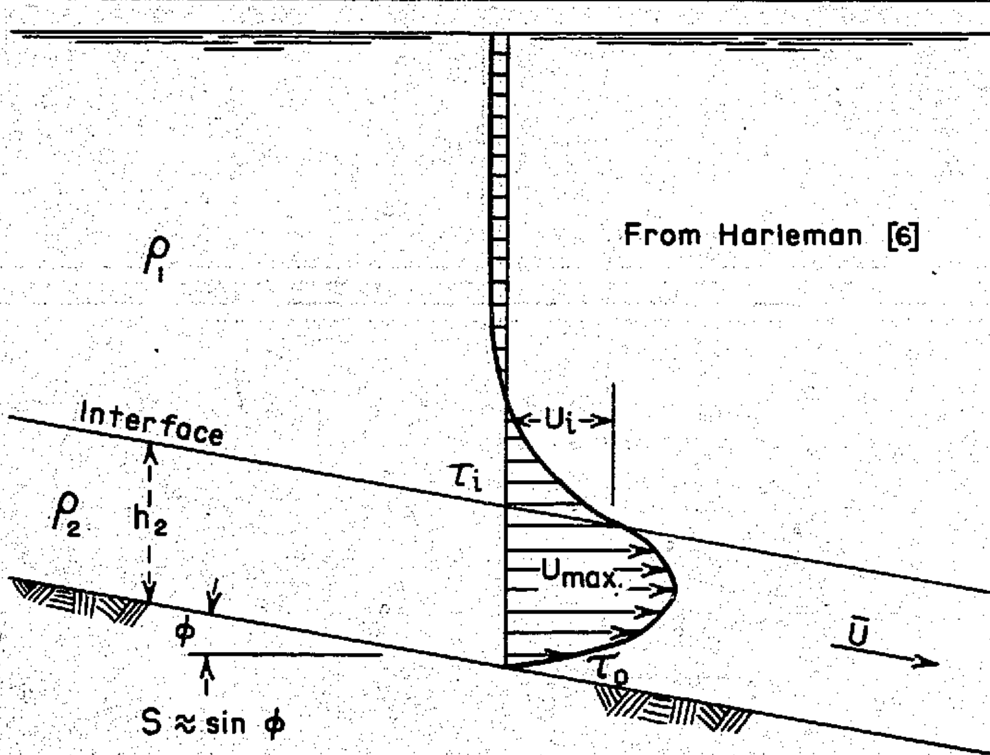

FIGURE 2— STEADY, UNIFORM FLOW IN LOWER-LAYER FLUID

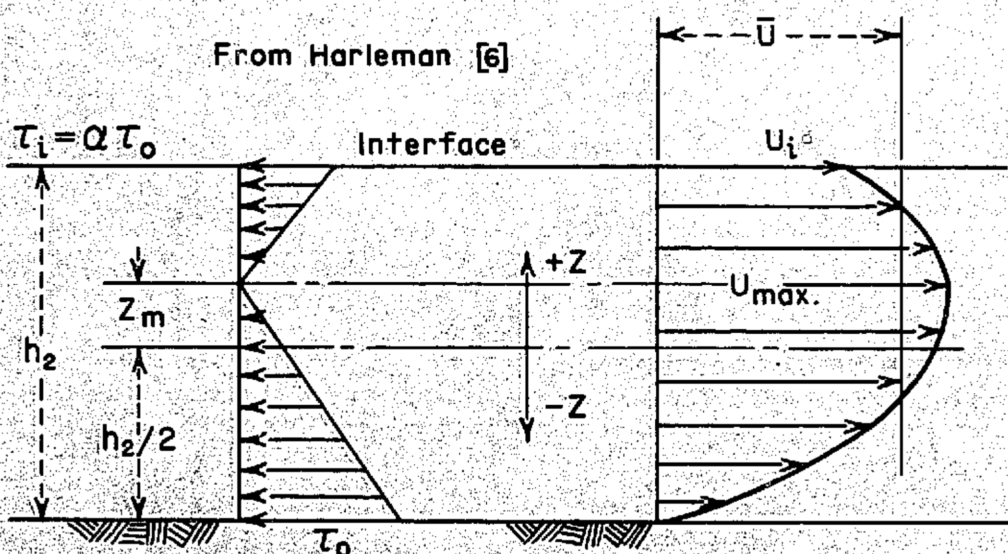

FIGURE 3—SHEAR-VELOCITY DISTRIBUTION IN LOWER-LAYER FLUID

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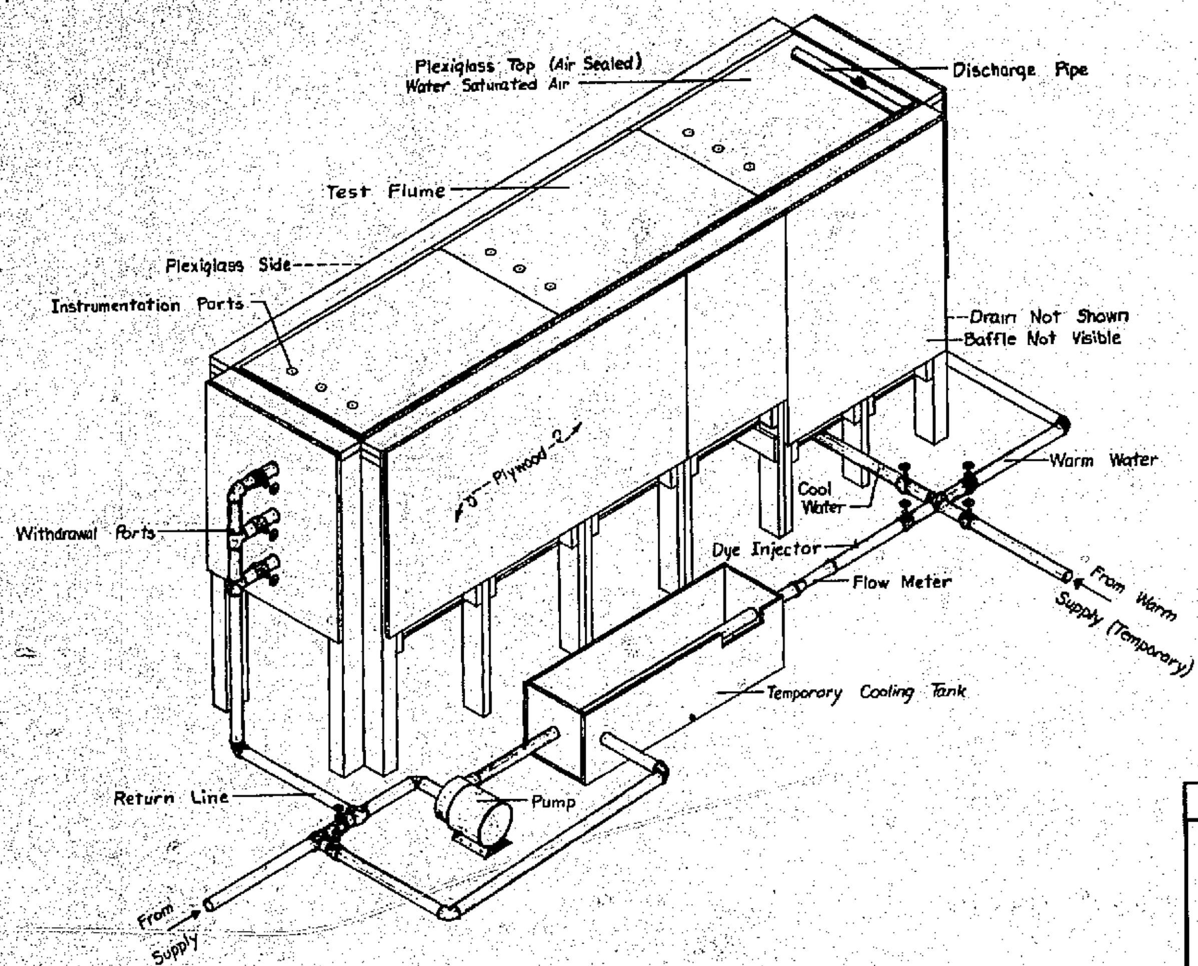
FIGURE 4
REPORT HYD-563



Scale : 1" = 2'-0"

ALWAYS THINK SAFETY

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

STRATIFIED FLOW STUDY - TESTING FACILITY

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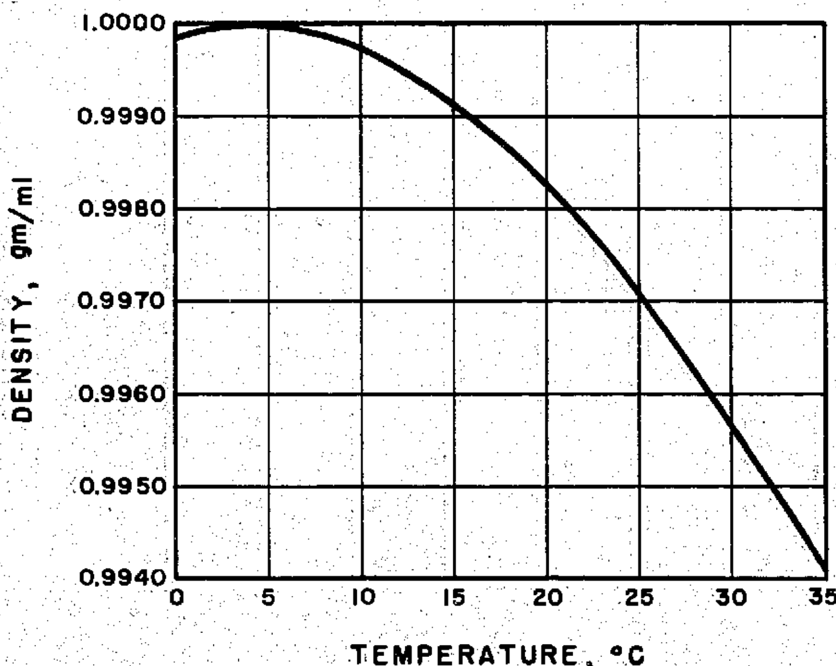

FIGURE 5—TEMPERATURE-DENSITY RELATIONSHIP FOR FRESH WATER

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(10-64)

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table 1

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03 (exactly)*	Square centimeters
	0.092903 (exactly)	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	9,463.58	Cubic centimeters
	0.946358	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^{6}	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^{7}	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second

Multiply	By	To obtain
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.02903* (exactly)	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

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ABSTRACT

A search of available literature on research in stratified flow revealed that the present state of research is dynamic, with many agencies and institutions in several countries involved. The report reviews the mechanics of stratified flow, including mathematical principles and criteria for similarity. Alternative instrumentation systems are discussed. The research activities of the Bureau of Reclamation are described and future research in hydraulics of stratified flow is proposed. Research by the Hydraulics Branch will consist of general studies concerning the influence of intake geometry on selective withdrawal from reservoirs. The initial studies will be extended to determine the effects of reservoir geometry. Gives 89 references.

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DESCRIPTORS-- research and development/ reservoirs/ density currents/ *hydraulic models/ hydraulic similitude/ hydraulics/ instrumentation/ temperature sensors/ thermocouples/ *water quality/ *stratification/ thermistors/ Froude number/ velocity distribution/ turbulent flow/ temperature/ energy/ salinity/ sediment concentration/ flow/ turbidity/ bibliographies/ reviews
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